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Engines & Energy Conversion Laboratory

Fundamental Studies of Ignition Process in Large Natural Gas Engines Using Laser Spark Ignition

Dr. Bryan Willson, Principal Investigator
Tom J. George, Project Manager, DOE/NETL
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Cooperative Agreement DE-FC26-02NT41335
Awarded 5/1/02, 24 months
$736,839 Total Contract Value ($500,000 DOE)

WOODWARD

DRESSER
Waukesha

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Knowledge to Go Places

Outline

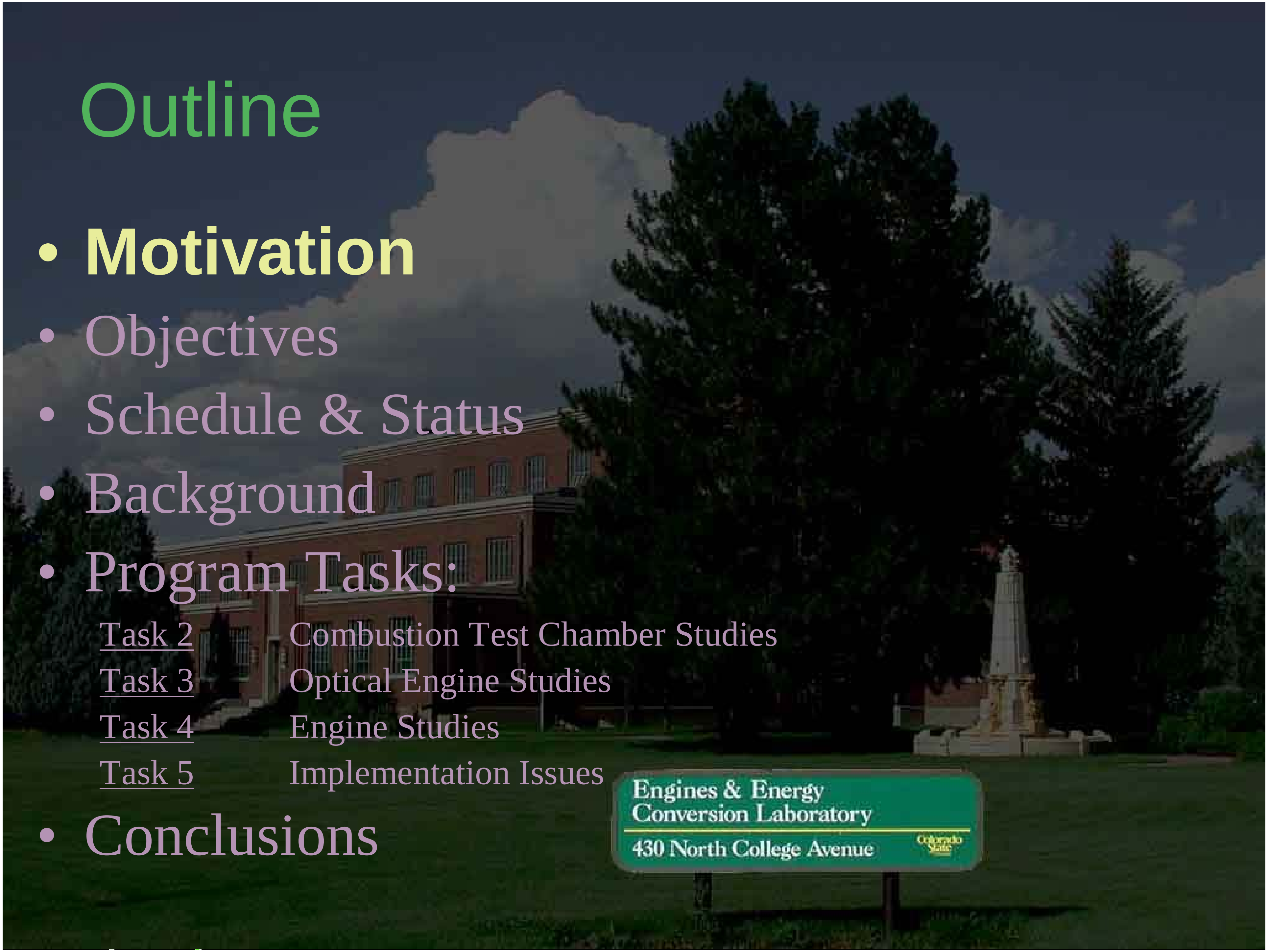
- **Motivation**
- Objectives
- Schedule & Status
- Background
- Program Tasks:

  <u>Task 2</u> Combustion Test Chamber Studies

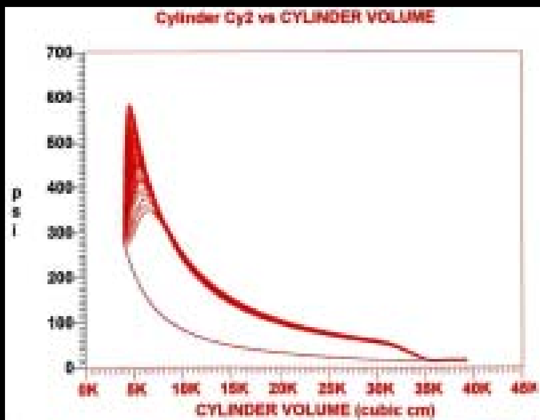
  <u>Task 3</u> Optical Engine Studies

  <u>Task 4</u> Engine Studies

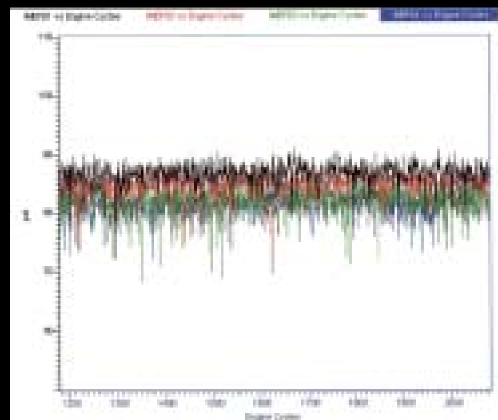
  <u>Task 5</u> Implementation Issues
- Conclusions



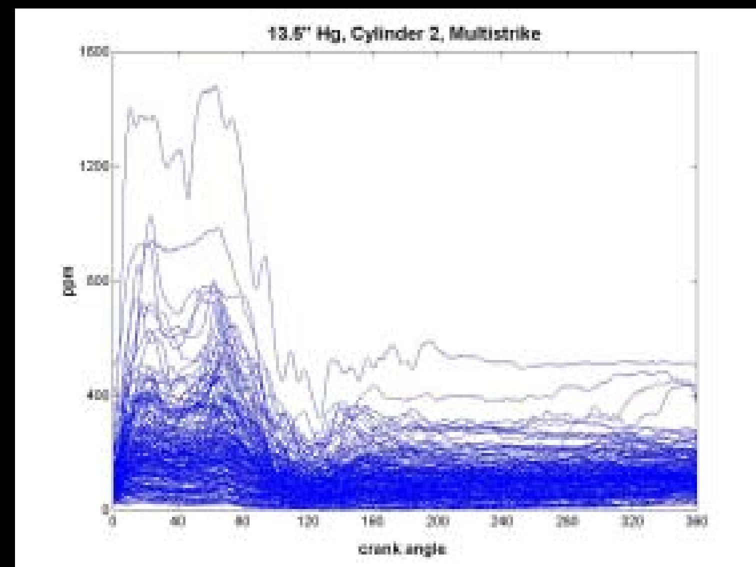
Motivation: Increased Combustion Stability



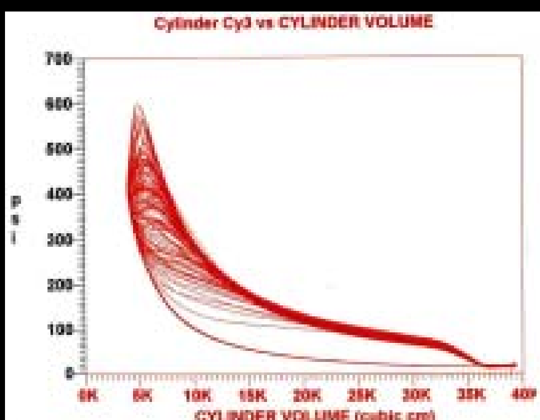
PV Diagrams
Stable Combustion



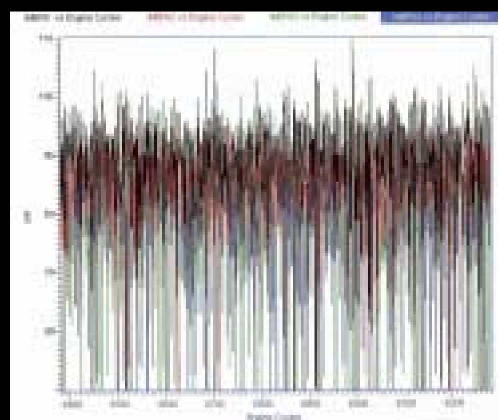
IMEP
Stable Combustion



Cyclic Variations of NOx

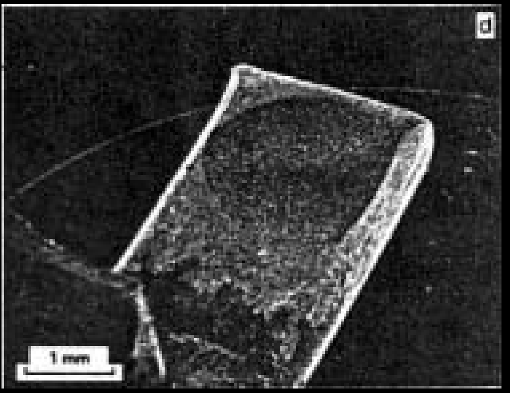


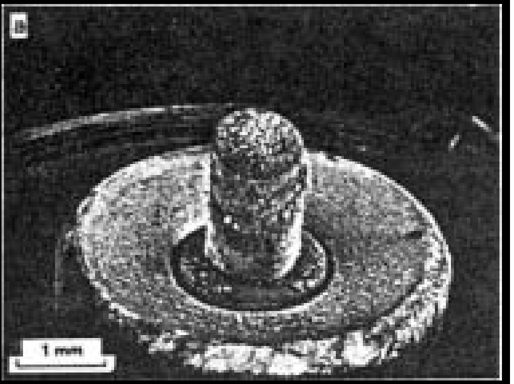
PV Diagrams
Near Lean Limit

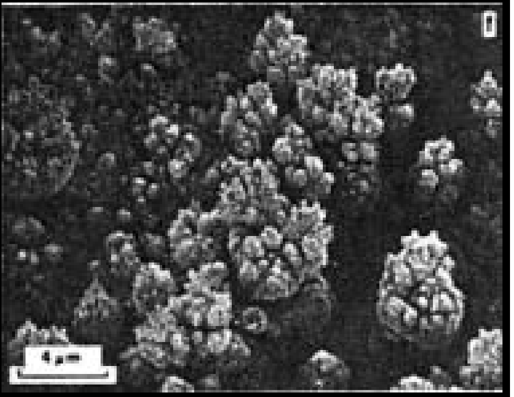


IMEP
Near Lean Limit

Motivation: Avoid Spark Plug Erosion







Spark Plugs

- Significant erosion problems for lean-burn, high-bmep engines
- Problem is exacerbated as in-cylinder pressures rise

Laser Ignition

- Unaffected by erosion
- Ignition becomes easier as in-cylinder pressures rise

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  Task 4 Engine Studies

  Task 5 Implementation Issues
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Project Objectives

- Generate fundamental data on ignition processes in order to quantify the fundamental physics of the establishment of a flame kernel, initial growth of the flame kernel, and transition to a propagating flame
- Quantify potential benefits (emissions, efficiency, combustion stability) from the use of laser ignition in a high-bmep, lean-burn natural gas engine
- Work jointly with laser manufacturers, engine manufacturers, and ignition system manufacturers to identify implementation breakthroughs needed before laser-base ignition can be applied to production engines.

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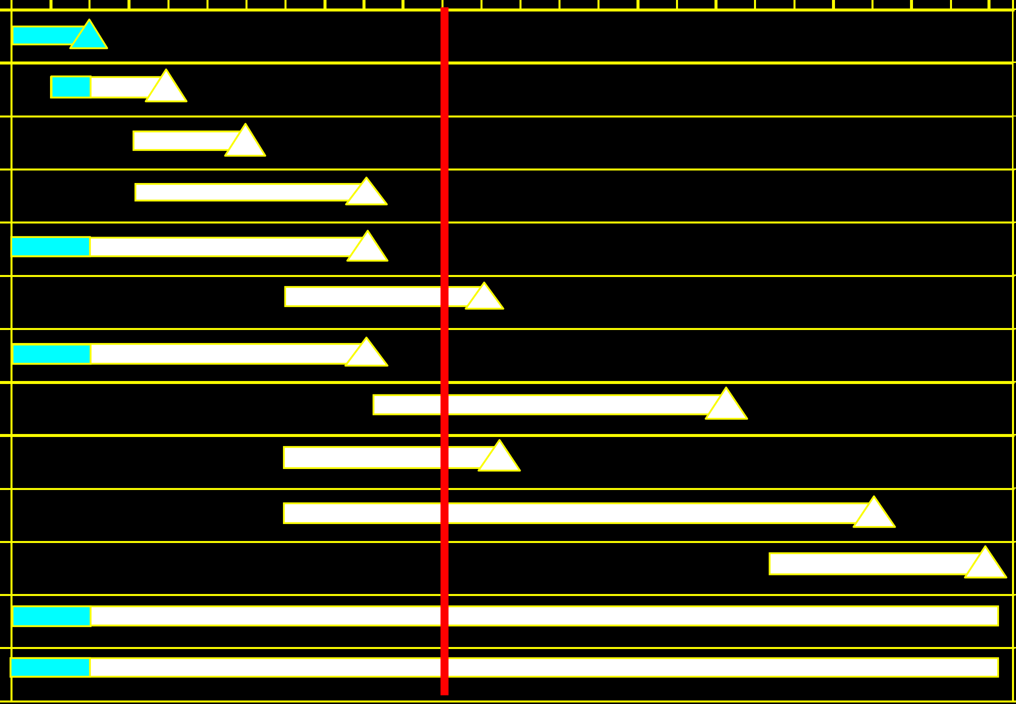
Project Schedule

1. Program/Project Identification No.	2. Program/Project Title
DE-FC26-02NT41335	Fundamental Studies of Ignition Processes in Large Natural Gas Engines Using Laser Spark Ignition

3. Performer (Name, Address)	4. Program/Project Start Date / 5. Program/Project Completion Date
Colorado State University / Engines & Energy Conversion Laboratory, attn: Ted Bestor Mechanical Engineering Department Fort Collins, 80523-1374	4. May 1, 2002 5. May 1, 2004

8. Program/Project Duration: 24 months

M J J A S O N D J F M A M J J A S O N D J F M A M



6. Identification Number		7. Planning Category (Work Breakdown Structure Tasks)	9. Comments (Notes, Name of Performer)
1	1	Prepare Milestone Plan and Explain	CSU
2	2a	Combustion Test Chamber Fabrication	CSU
3	2b	Quiescent Combustion Test Chamber Baseline	CSU
4	2c	Turbulent Combustion Test Chamber Studies	CSU
5	3a	Optical Engine Fabrication	CSU
6	3b	Optical Engine Combustion Test Chamber Studies	CSU
7	4a	Engine Modification & Install	CSU
8	4b	Engine Tests	CSU
9	5a	Alternative Laser Selection	CSU
10	5b	Fiber Optic Delivery	CSU
11	5c	Sooting Studies	CSU
12	6a	Project Management	CSU
13	6b	Education	CSU

10. Remarks

11. Signature of Recipient and Date

12. Signature of U.S. Department of Energy (DOE) Reviewing Representative and Date

Schedule Summary & Status

Task 1 - Milestone Plan
On schedule

Task 2 - Combustion Test Chamber Studies
Schedule Slip

Task 3 - Optical Engine Studies
Project Modification

Task 4 - Engine Studies
On Schedule

Task 5 - Implementation Issues
Ahead of Schedule

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Task 4	Engine Studies
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Laser Ignition Methods

LI Photochemical

IR or UV multi-photon absorption photo-dissociation of specific molecular species

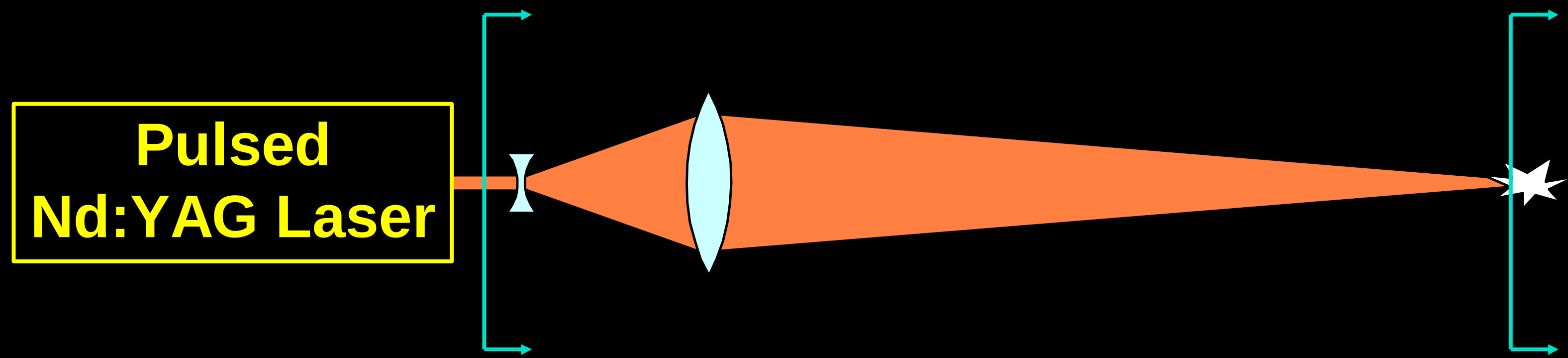
LI Thermal

Refers to the use of IR absorption (typically CO laser) to vibrationally excite specific molecular species leading to heating of gas to point of thermal ignition

LI Spark

High power, pulsed laser producing large electric fields which cause local gas breakdown leading to high temperature plasma

Laser Spark Metrics



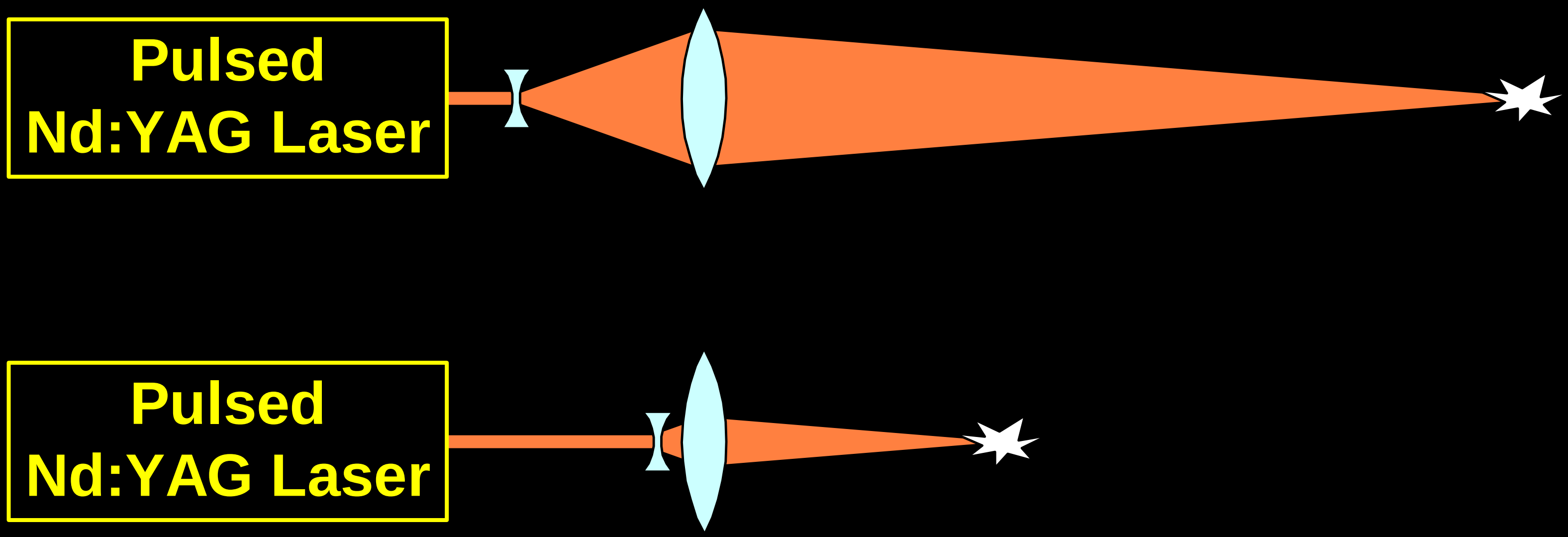
Initial beam density ≈50 MW/cm^2

Breakdown occurs when beam is concentrated to ≈10,000 MW/cm^2

Laser Parameters

Pulse Energy:	50 mJ	Pulse Duration:	5 ns
Beam Diameter:	2.5 mm	Beam Area:	0.2 cm^2
Pulse Power:	50 mJ / 5 ns = 10 MW		
Energy Density:	10 MW / 0.2 cm^2 = 50 MW/cm^2		

Variable Focal Length



The ability to vary the focal length and place the spark at an arbitrary location away from the cylinder walls is believed to be one of the most important benefits.

Demonstration of Laser Spark Creation (EECL Laser Lab)

Minimum Ignition Energy – Reported Results

- Laser Irradiance of 10^{12} to 10^{13} W/cm^2 (P. Tran)
- **3-4 mJ / 5.5ns** pulse for rich AFR, increased sharply to **40mJ / 5.5ns** pulse for leaner mixtures. (also P. Tran)
- 4-40mJ (CM Ho, NASA)
- 0.4 – 1.0mJ (Sloane) (This appears to be a combination of Thermal and Photochemical Ignition rather than Spark)
- 500 mJ / 1µs pulse (Schmieder, Sandia)

Laser Selection:
Open-Path vs. Fiber-Coupled

Open-Path
Flashlamp-Pumped Laser
(10 hz, 750+ mJ, 9 ns)

Fiber-Coupled
Flashlamp-Pumped Laser
(20 hz, 45 mj after fiber, 5-8 ns)

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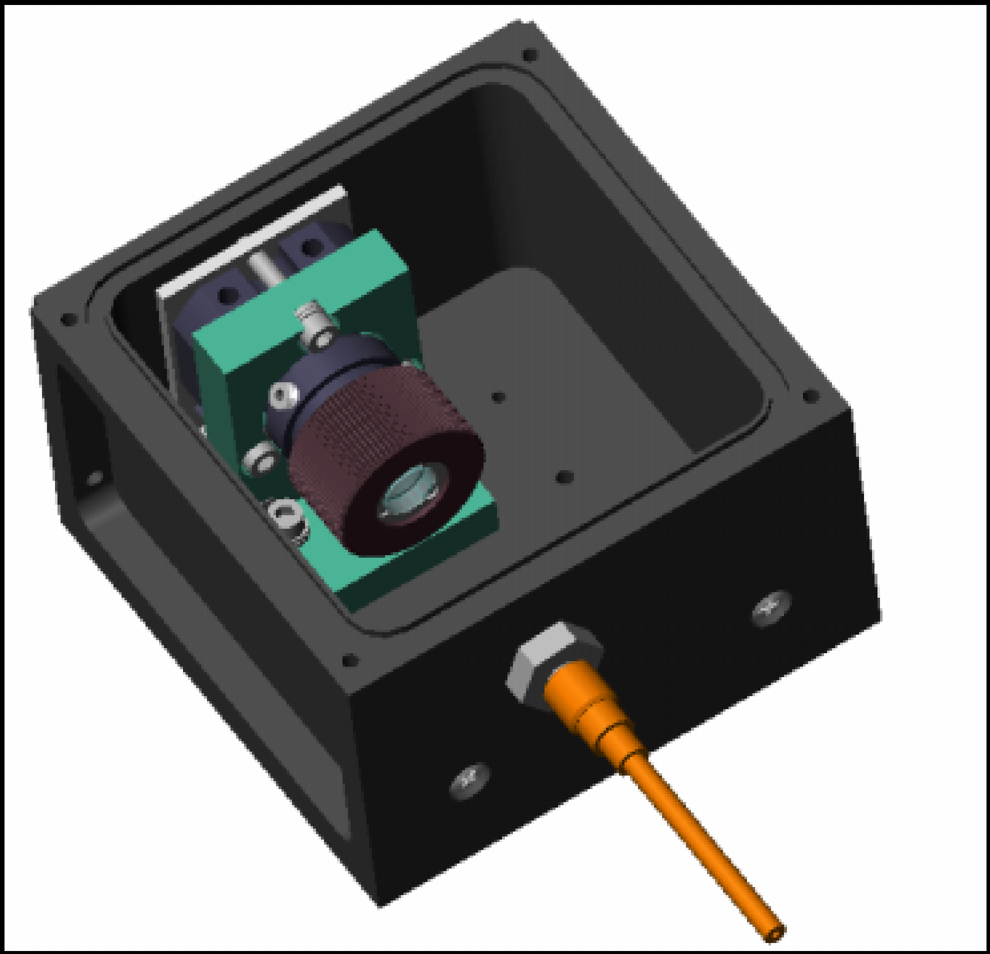
Fiber Optic Implementation



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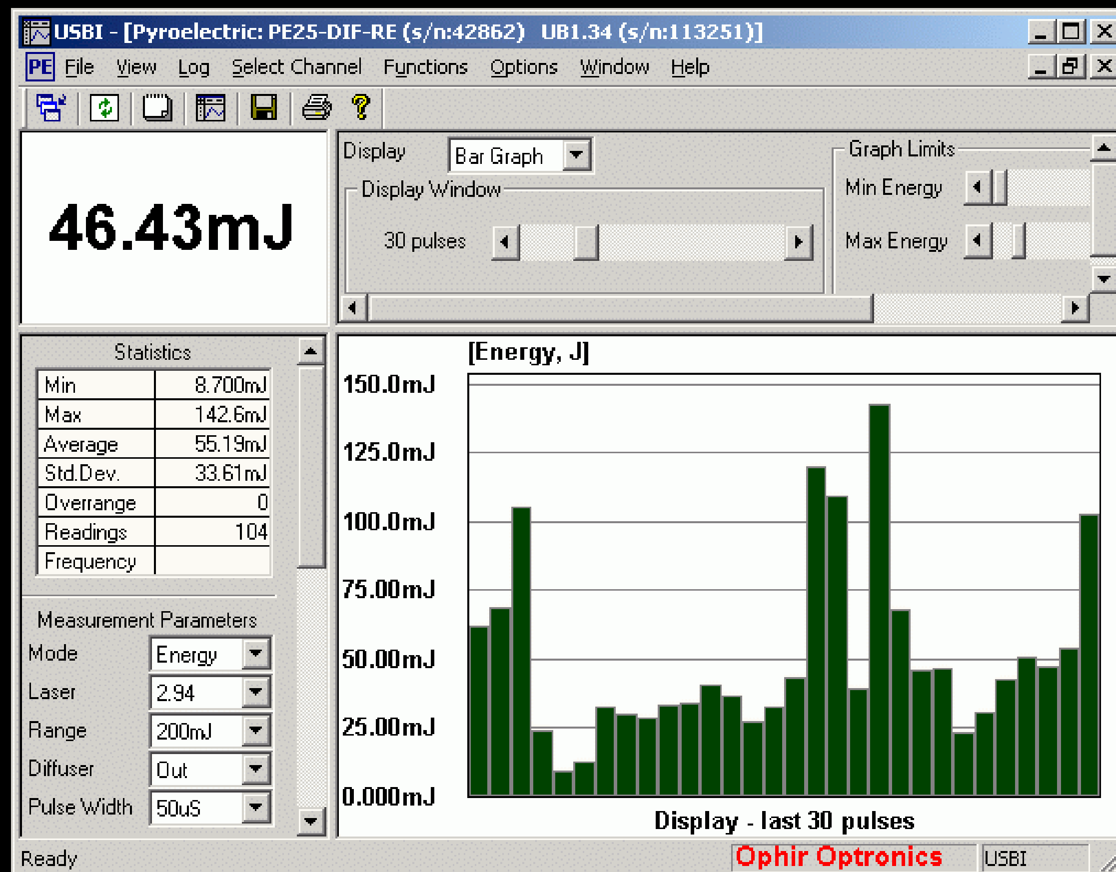
Laser Characterization



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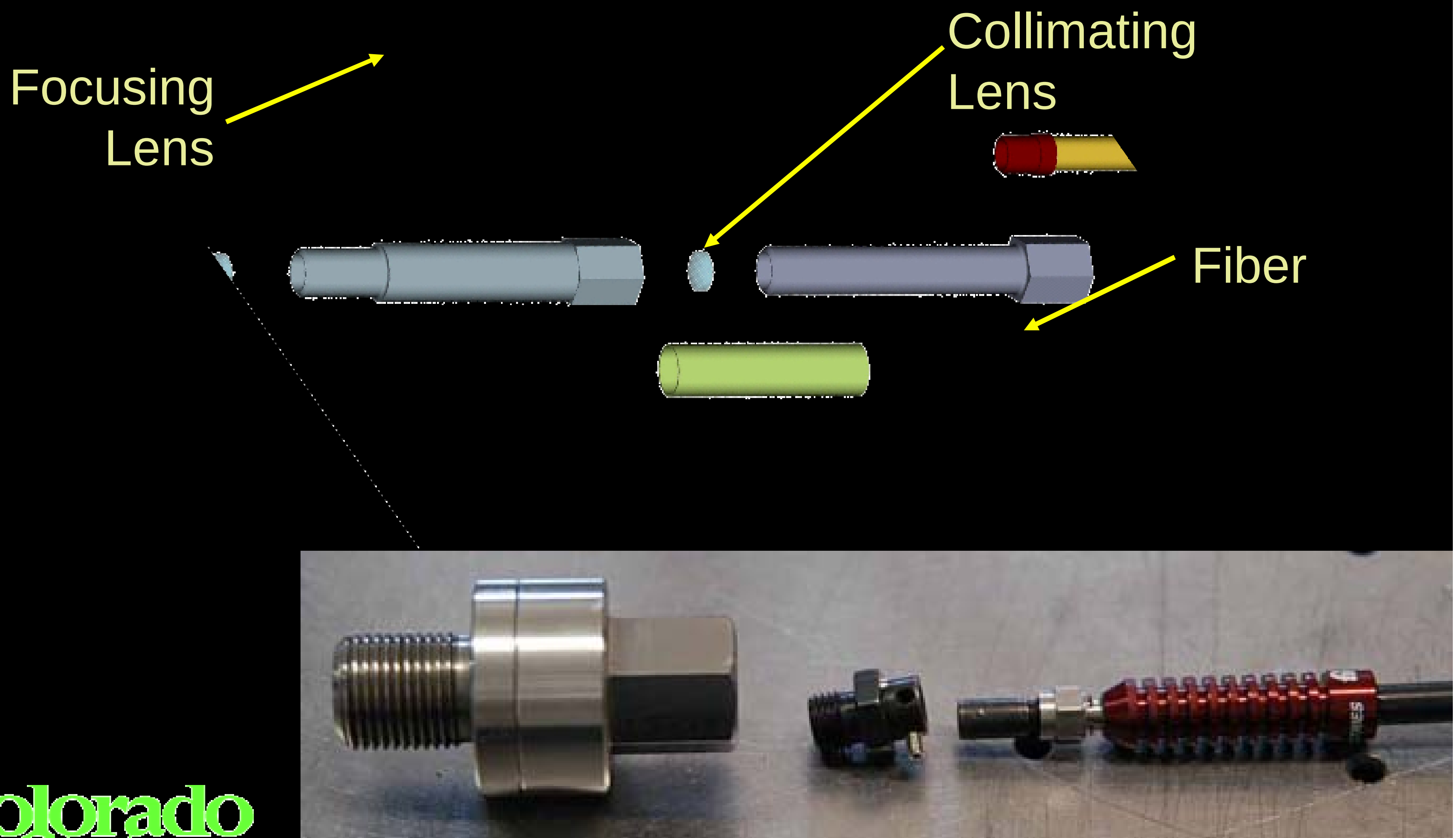
Laser Spark Plug



Mounting in CTC

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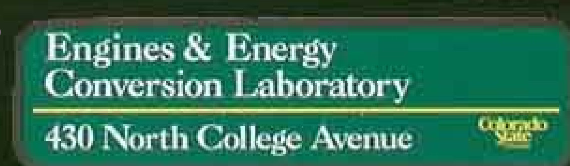
Task 2 **Combustion Test Chamber Studies**

Task 3 Optical Engine Studies

Task 4 Engine Studies

Task 5 Implementation Issues

- Conclusions



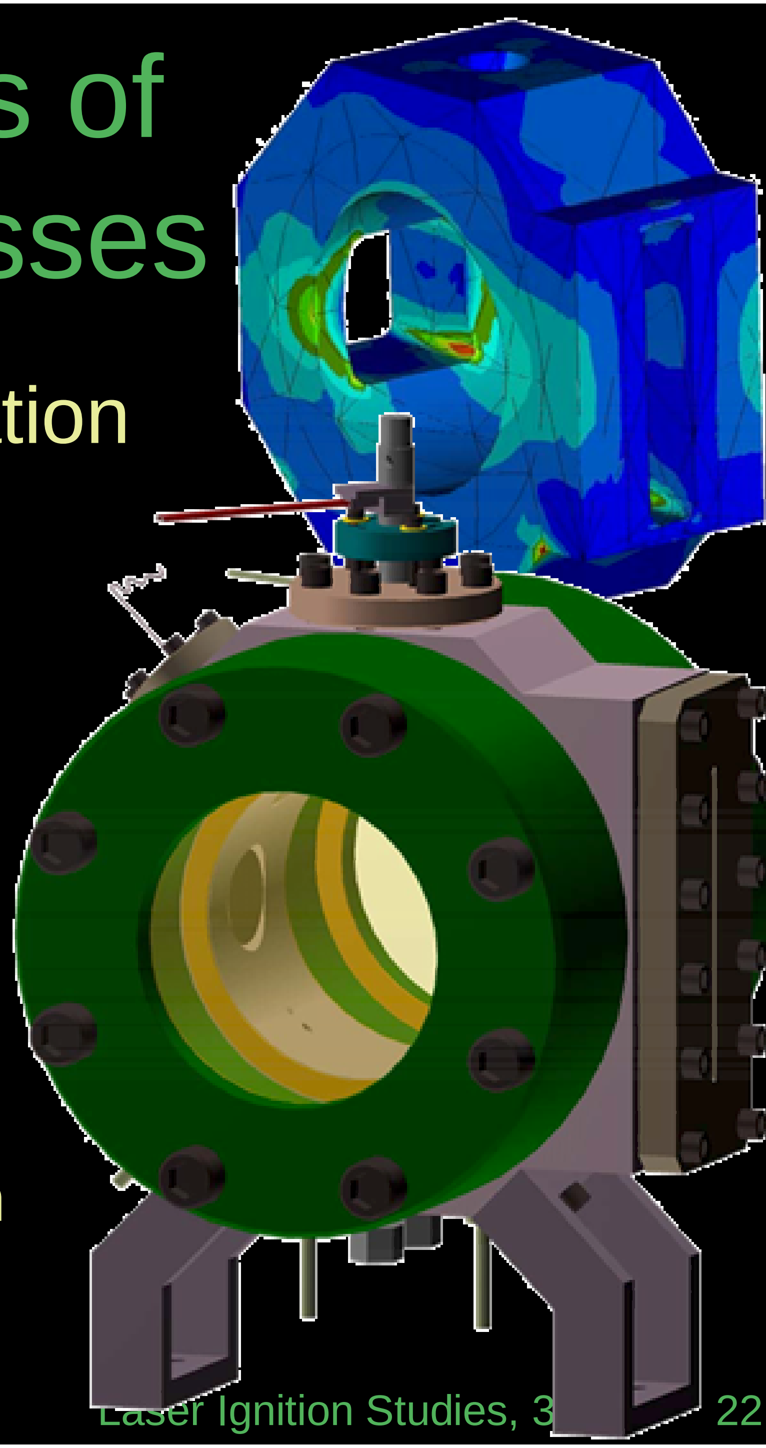
Task 2: CTC Studies of Early Ignition Processes

a) CTC Fabrication / Modification

b) Quiescent CTC Baseline

c) Turbulent CTC Studies

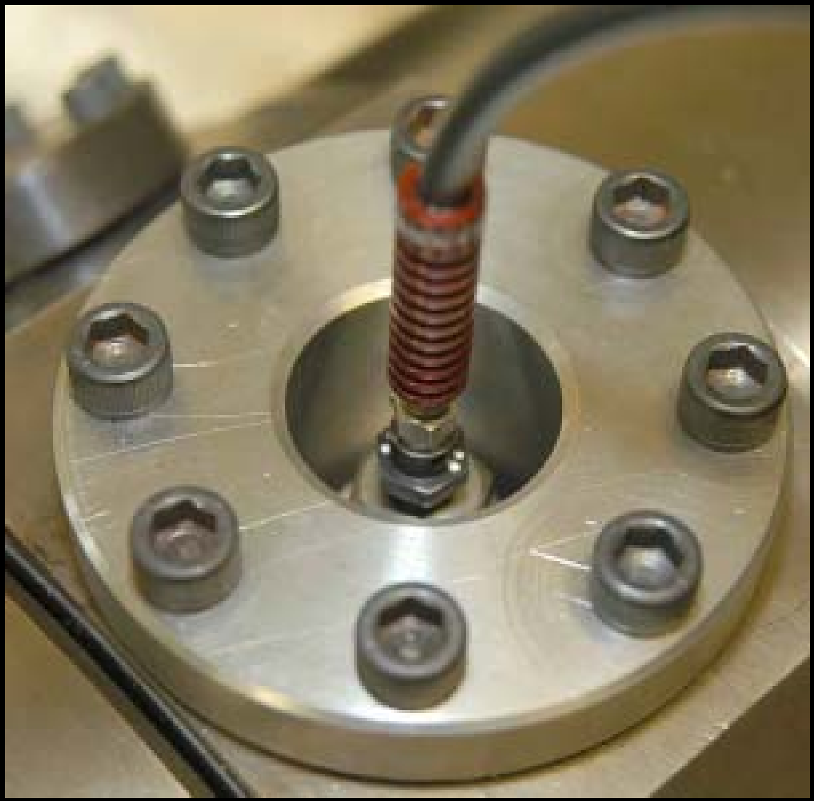
a) CTC fabrication / modification



CTC Investigations

- Minimum ignition energy
- Spark geometry vs. focal length
- Spark location effects
- Effect of frequency
- Effect of laser duration (flashlamp-pumped vs. diode pumped)
- Effects of turbulence intensity and scale

CTC Adapters



Fiber-Coupled Adapter

Open-Path Adapter

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Task 2: CTC Studies of Early Ignition Processes

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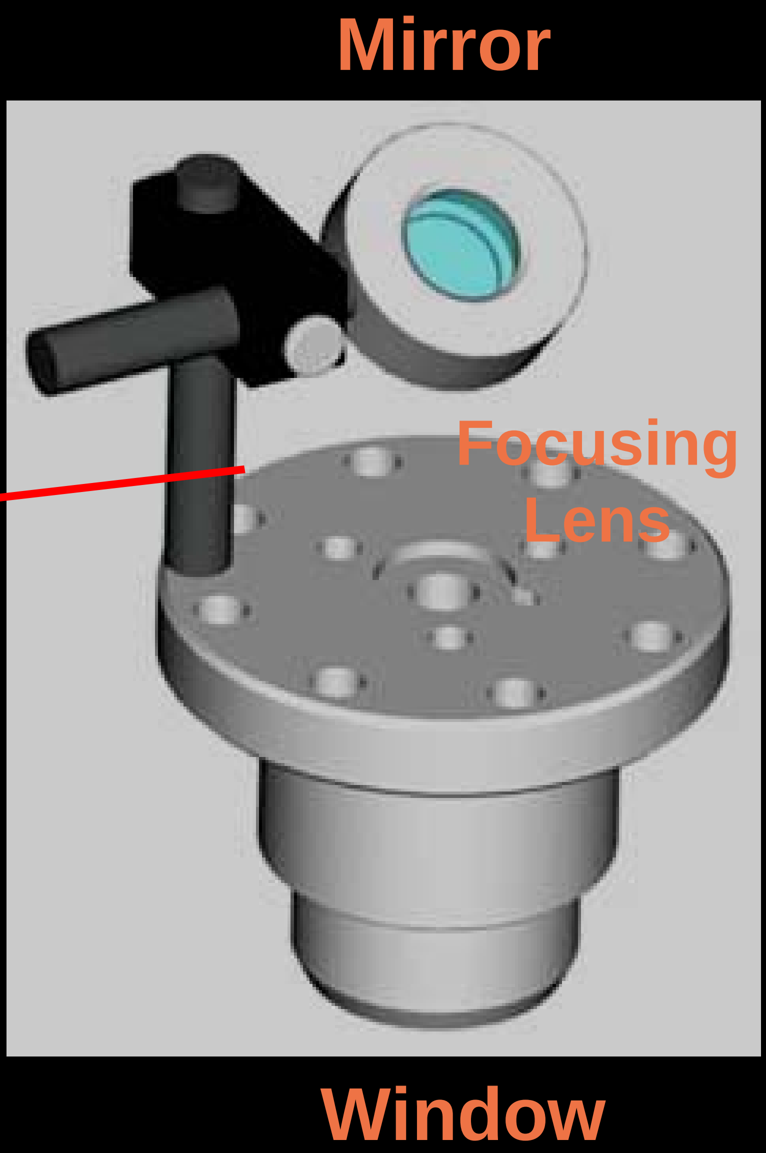
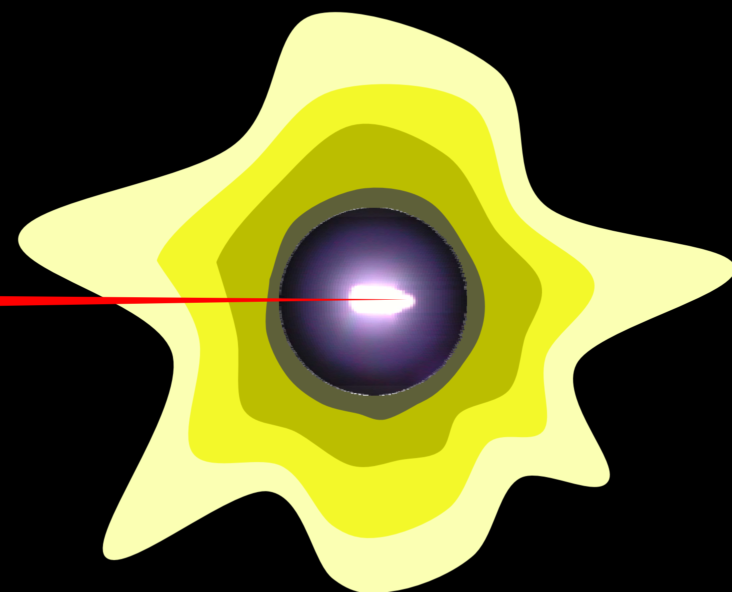
Laser
Adapter
Housing
for CTC



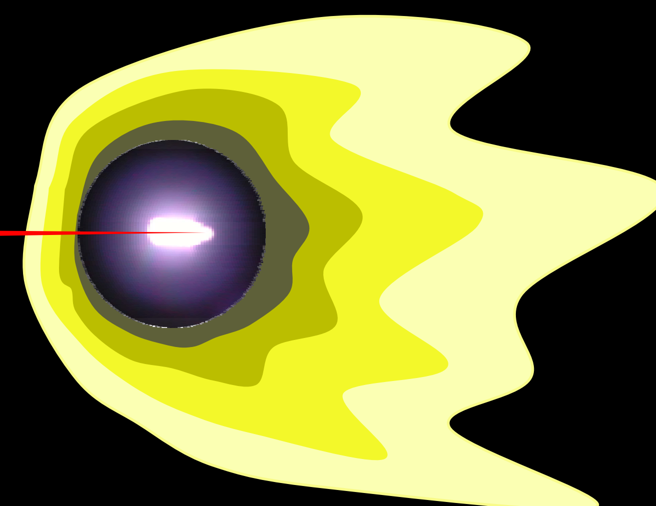
Fiber-Optic Laser Plug in CTC

Task 2: CTC Studies of Turbulence / Convection

b) Quiescent Baseline



c) Turbulent Studies



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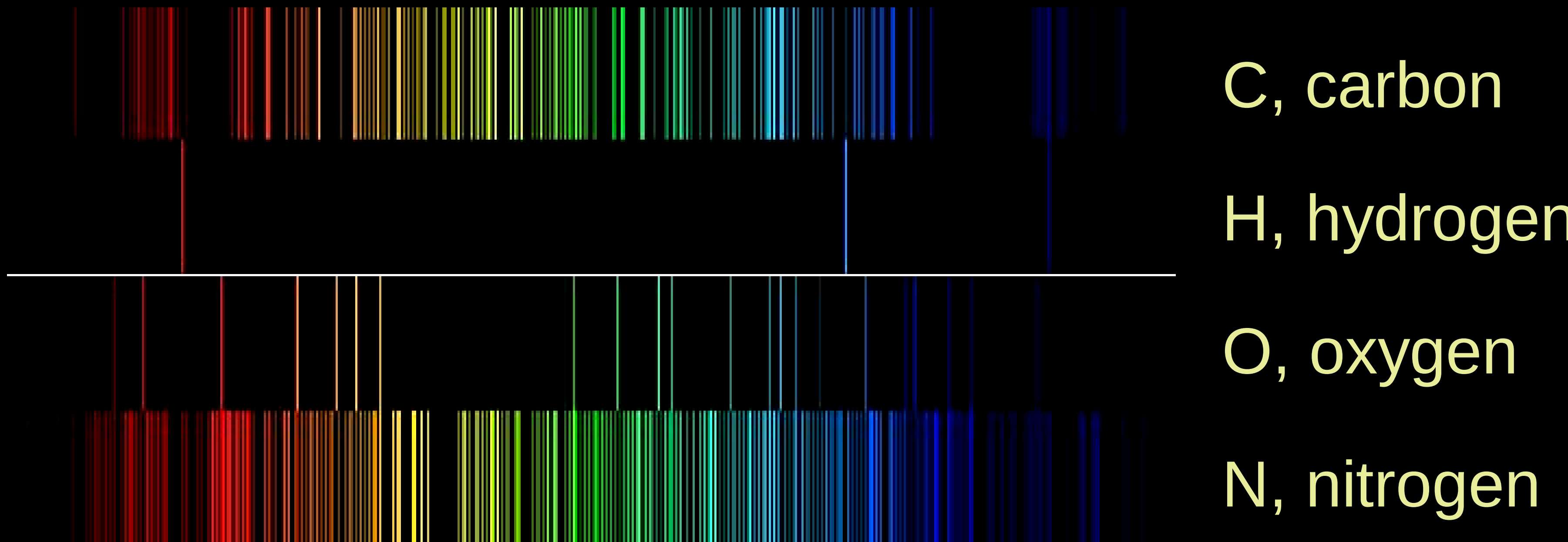
Effects of Focal Length on Spark Geometry

Short
Focal
Length

Long
Focal
Length?

Spark Diagnostics:
LIBS (Laser Induced Breakdown Spectroscopy)



- By analyzing the frequency spectrum of the light emitted from the spark, the ratio of C, H, O, & N can be determined. This information can be used in a carbon balance to determine A/F ratio.
- Emissions of OH can be used to monitor combustion.

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Task 3	**Optical Engine Studies**
Task 4	Engine Studies
Task 5	Implementation Issues

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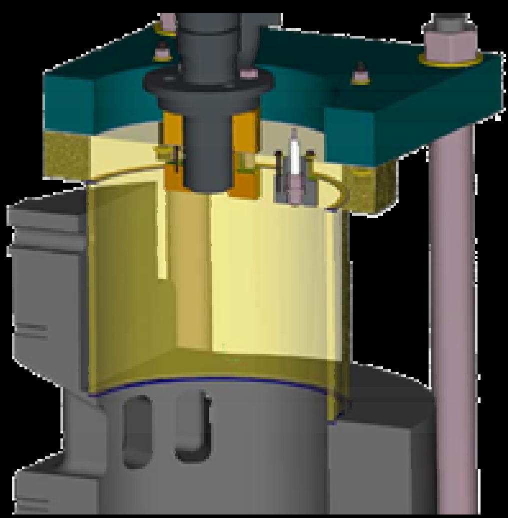
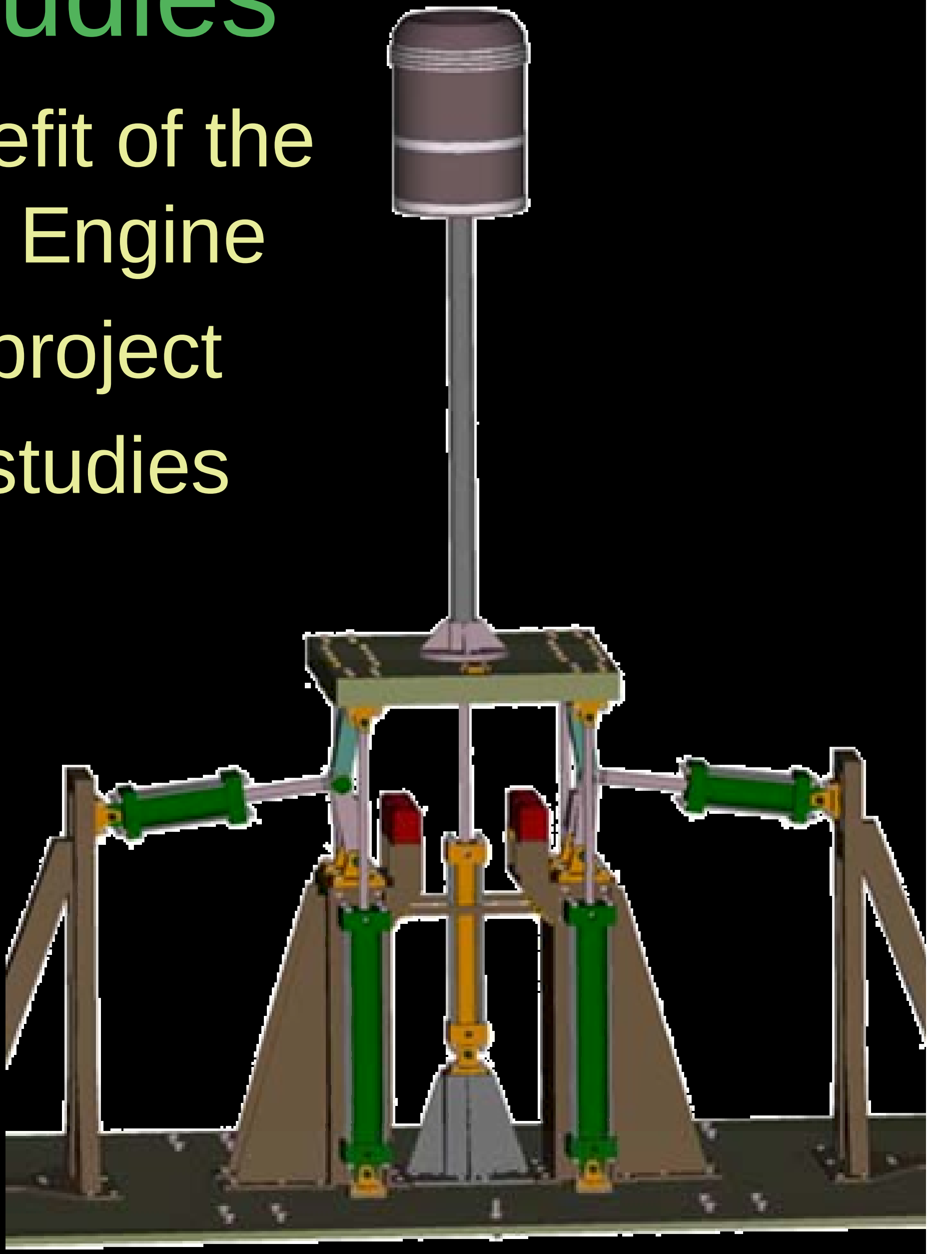
Optical Engine Studies

- Scheduling depends on refit of the EECL's Large Bore Optic Engine
- Moved to latter phase of project
- Allows earlier on-engine studies





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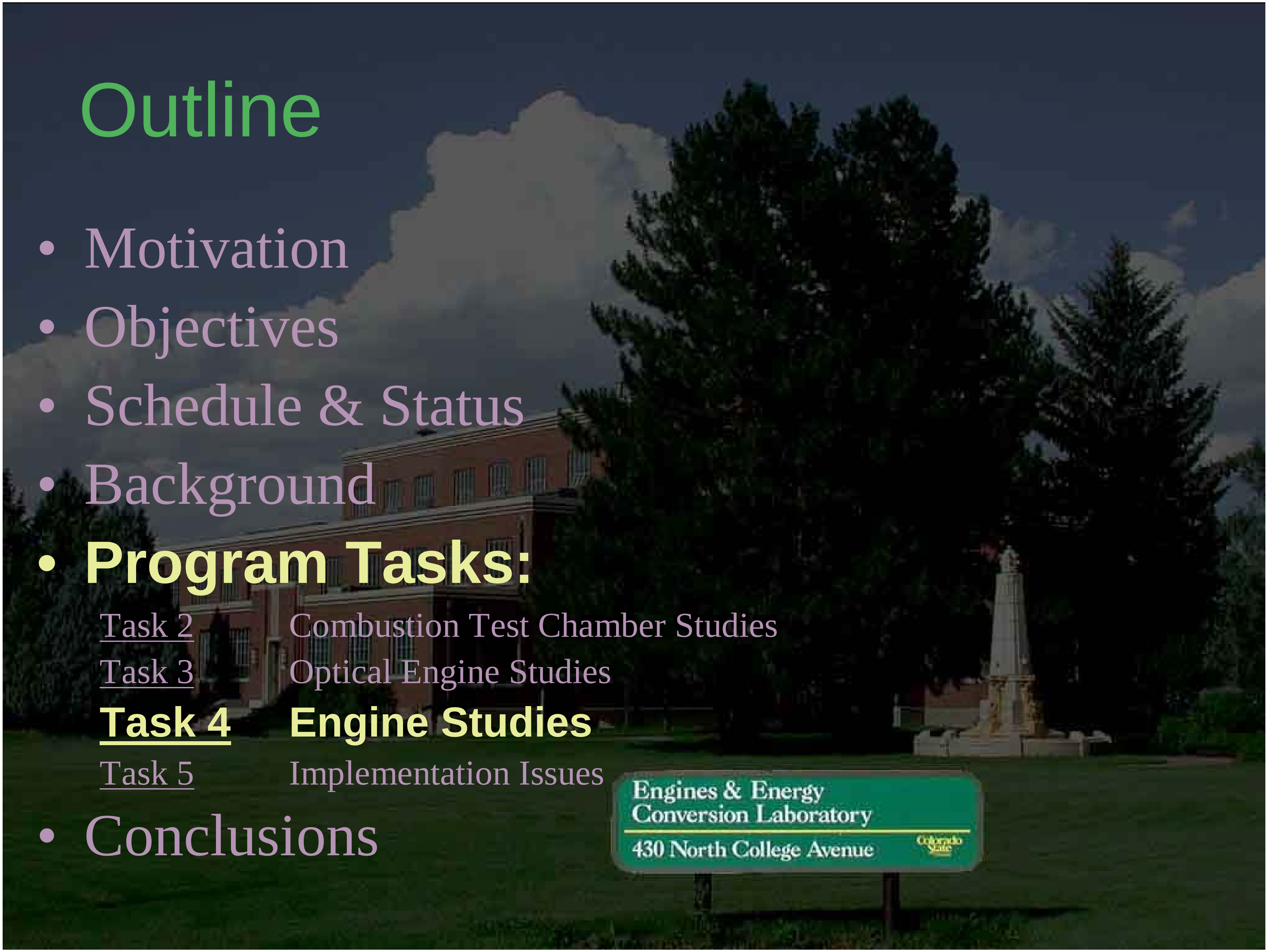
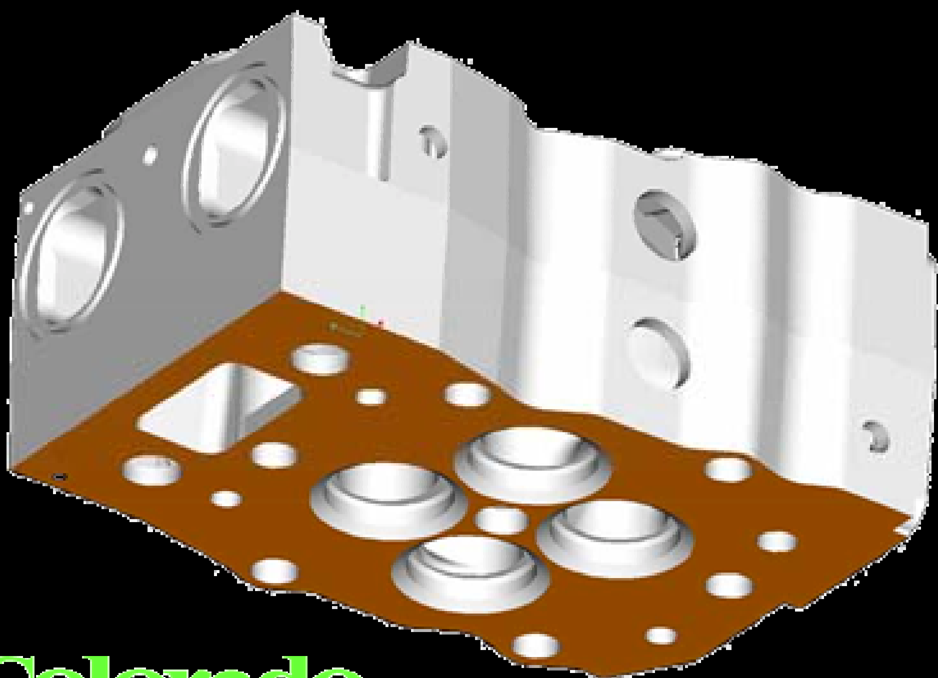


Task 4: Engine Tests

1. Installation of Waukesha F-18 Engine
2. Engine Tests



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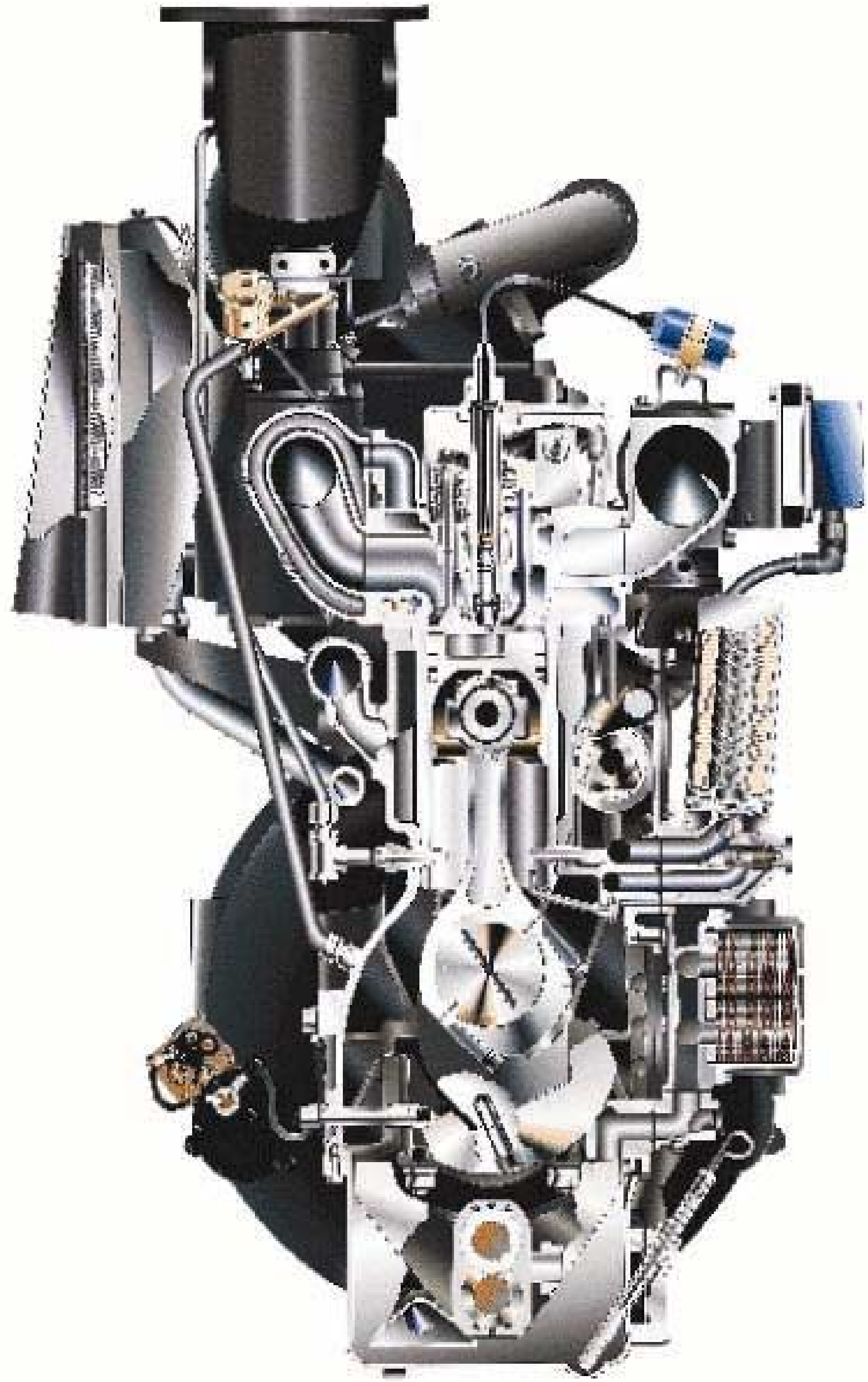

Engine Complete & Operational

F-18 Engine Installation

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Controls & Data Acquisition

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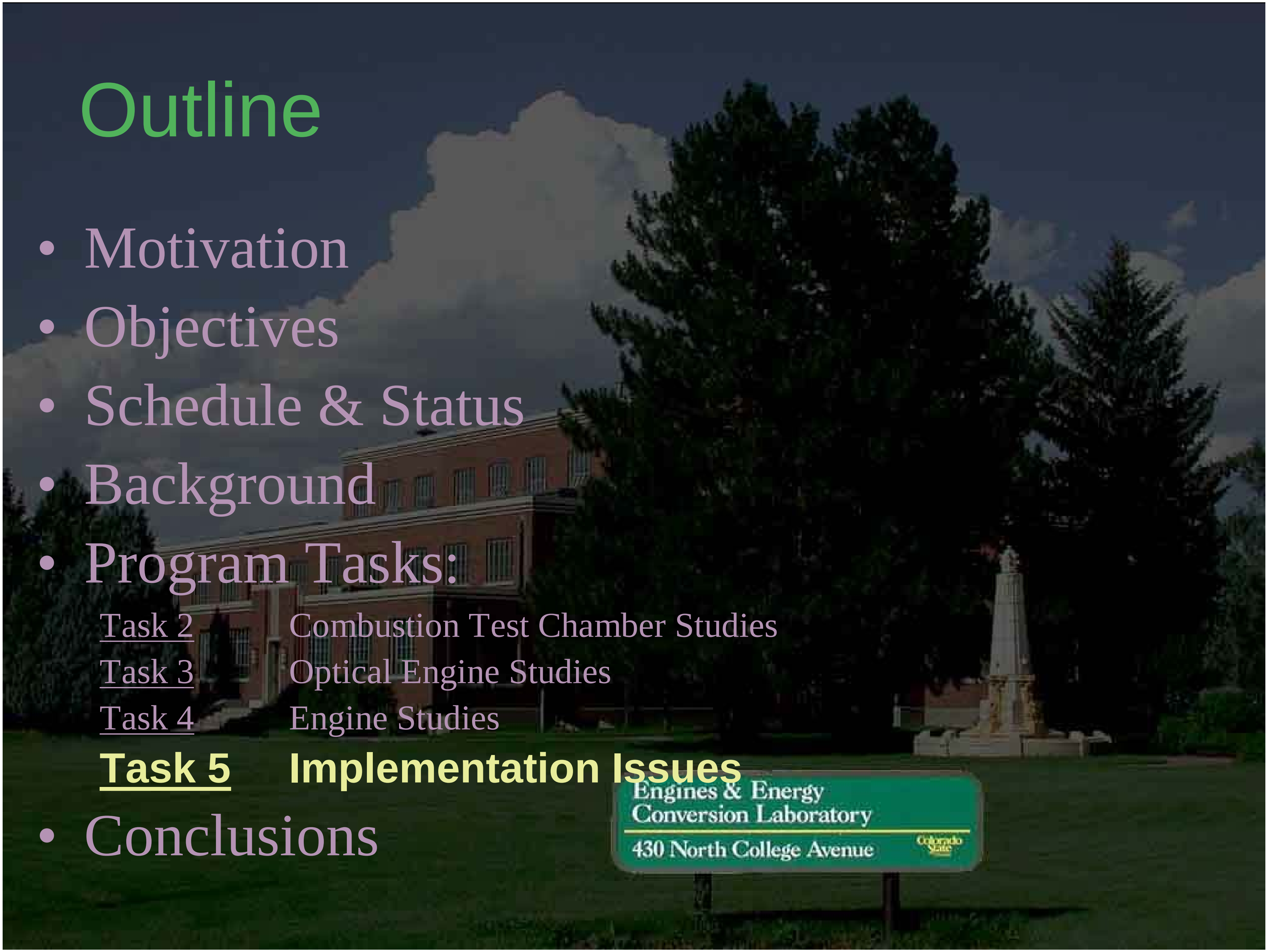
- Conclusions



Task 5: Implementation Analysis

a) Alternative Laser Selection
b) Fiber Optic Delivery
c) Sooting Analysis

Alternative Laser Selection

Fiber-Coupled
Diode-Pumped
Solid-State Laser

Fiber-Coupled
Flashlamp-Pumped Laser

Open-Path
Flashlamp-Pumped Laser

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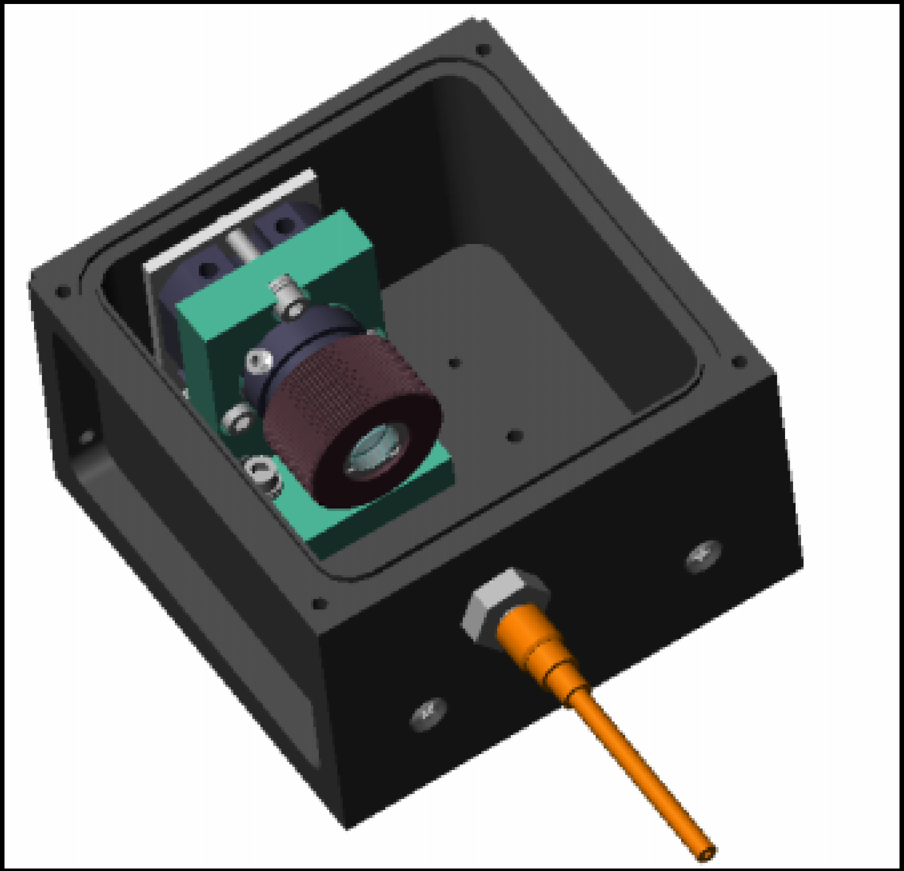
Fiber Optic Implementation



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Sooting Studies

Note: Even with sooted lens, the system continued to spark consistently

Sooted Lens

Lens Showing Soot Ablation after 10 Laser Pulses

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Accomplishments / Conclusions

- Waukesha F18 test engine installed and operational
- Combustion test chamber operational
- Initial qualitative open-path studies complete
- Fiber-optic coupled laser procured and operational
- Preparations for first fiber-optic engine and test chamber tests in final stage
- Completion of fabrication stage – beginning of quantitative stage!

Questions?

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Contact Information

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